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THE DEGREE OF SUSTAINABLE DEVELOPMENT PRINCIPLES IMPLEMENTATION IN TRANSPORTATION BASED ON AN ECONOMIC ANALYSIS OF RAIL BUSES' LIFE CYCLE

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ABSTRACT: The article presents an economic analysis of the life cycle of rail buses. As this analysis part, the costs incurred by the user in the exploitation phase of a rail bus were assessed. The cost estimate was based on the author's own method of forecasting the exploitation costs of a technical object (e.g. means of transport, equipment, machinery), which takes into account the variability of the costs incurred over time. The article also provides the implementation of the aforementioned method, verifying its practical application when estimating the exploitation costs of technical objects. Experimental verification aimed at assessing the usability of the cost forecasting method is the purpose of this article.

The verification was carried out for eight single mode X type rail buses produced by the same manufacturer. The experimental verification of the method used to estimate exploitation costs in the life cycle of objects consisted in: 1. Conducting reliability analysis of the exploitation objects in order to obtain data of technical and economic nature; 2. Entering data into the method and calculating cost forecasts; 3. Assessing correctness of the results.

The degree of accuracy of the exploitation cost forecast was measured using ex post relative forecast error. The compatibility analysis of the forecast cost values with the actual ones showed their high compatibility, as evidenced by the level of the estimated relative errors (the average error was 4.9%). Therefore, it can be concluded that the prognostic value of the method is relatively high.

KEYWORDS: Life Cycle Cost Analysis (LCCA), exploitation cost, rail buses, sustainable transport

Introduction

Rail buses are diesel-powered vehicles used to handle traffic on non-electrified lines and those with smaller passenger flows. These vehicles represent the means of transport characterised by high ecological values, which result, i.a. from their high transport capacity, punctuality of transport (due to the absence of traffic congestion) as well as the limited impact on environmental pollution. Therefore, a rail bus is a means of transport that implements, to a very significant extent, the assumptions of sustainable transport, i.e. the one which considers not only the economic aspect but also some environmental and social factors (Dzwonkowska, 2013).

To assess the degree of implementation of sustainable transport principles, an integrated analysis of the life cycle of a technical object (in this case, a means of transport) can be used. In each of the object life cycle phases (figure 1), separate activities are carried out, generating costs and remaining the source of various types of emissions. Each type of emission has a different, specific impact on the environment.

In the engineering design phase, both the raw materials and components to be used in the production of an object, as well as the technological process are selected. In the next phase of the life cycle, raw materials are obtained (extraction and processing), and the construction of a technical object in
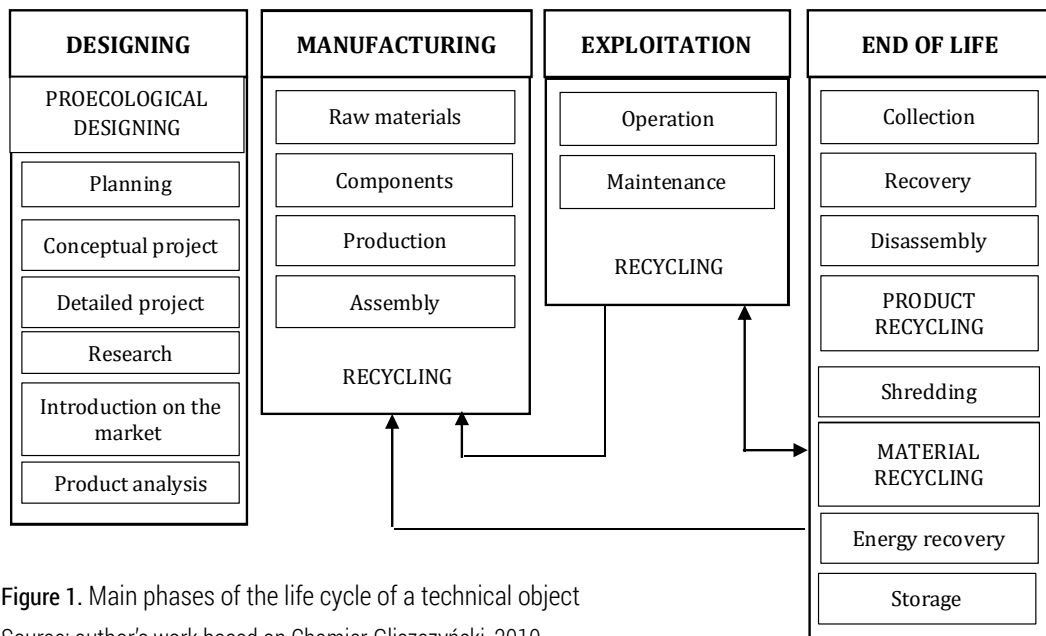

Figure 1. Main phases of the life cycle of a technical object

Source: author's work based on Chamier-Gliszczyński, 2010.

accordance with the prepared design takes place. The exploitation phase is the subsequent stage of a technical object life cycle, in the course of which an object performs these tasks for which it was designed and manufactured (Woropay, 1996). Finally, the life cycle finishes with the end of life phase, during which the activities related to the end of life of a technical object are performed. As shown in figure 1, in all phases of the product life cycle (design, production, operation and end of life), there are opportunities for their pro-ecological rationalisation.

The integrated life cycle analysis, which includes Life Cycle Cost Analysis (LCCA), Environmental Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA), is one of the basic methods to support making investment decisions. This analysis helps to choose the means of transport which is the most economically efficient and the least harmful to the environment and society. It takes into account all costs and burdens incurred in the life cycle of each of the assessed purchasing alternatives and not just the direct costs of the purchase. Therefore, the integrated life cycle analysis covers both producer and user costs as well as social and environmental costs and burdens.

Because the social and environmental analysis of the life cycle of rail buses is currently in its preliminary research phase, this article presents an economic analysis of the life cycle of the above-mentioned technical objects. Within the framework of this analysis, the costs incurred by the user in the exploitation phase of a rail bus were assessed. To estimate the costs, the author's own method of forecasting the exploitation costs of a technical object was used, which allows conducting a comparative analysis of the alternative purchasing options. The article also provides the implementation of the aforementioned method verifying the possibility of its practical application when estimating the exploitation costs of technical objects. The verification was carried out for single-mode X type rail buses produced by the same manufacturer.

Exploitation costs of technical objects in LCCA – theoretical issues

From a customer's perspective purchasing a new technical object, the exploitation costs account for a significant part of its life cycle costs. It results from the fact that the exploitation covers approximately 90% of an object's entire life cycle duration (Młyńczak, 2012). Therefore, it is primarily the exploitation costs that should be analysed when assessing the effectiveness of alternative investments (pursuing the same goal). The assessment of exploitation costs allows eliminating the acquisition of cheap technical

objects regarding their purchase costs; however, expensive in their exploitation.

As opposed to purchase costs, exploitation costs are recurring and spread over time, hence difficult to estimate. However, estimating exploitation costs, based on the results obtained from the previously conducted exploitation analyses of technical objects, unquestionably increases the accuracy of their level measurement (Dziaduch, 2011a).

The source literature studies of the area under analysis confirm that one of the most important tasks in LCC modelling is to determine the cost breakdown structure (Cieślak, 2008; PN-EN 60300-3-3, 2001; Sarama, Adeli, 202; Świderski, 2003). It consists of breaking down the cost categories into lower-division levels (the so-called components of a given cost category) until the lowest level is achieved, the so-called cost parameter. A cost parameter is a value that cannot be determined by the sum of other costs. It is defined using mathematical formulas containing functions and constant values, e.g., the person-hour cost of maintenance personnel, the labour intensity of maintenance, etc. (Szkoda, 2007). An example of the breakdown structure of a technical object exploitation cost is presented in figure 2.

The estimation of cost components and parameters is based on analytical expressions defined or selected from the source literature by the researcher. The estimation methods of both the cost components and parameters of object exploitation are presented, e.g., in the study (Dziaduch, 2020b), whereas the methods for calculating the preventive maintenance cost components and parameters are addressed, i.a. in (Dhillon, 2007; Jong-Woon, Jong-Duk, Seok-Yun, 2009; Kumar, Chattopadhyay, Pannu, 2004; Norsok Standard: O-CR-001, 1996; PN-EN 60300-3-3, 2001; SINTEF Report, 1998). In the same studies and, e.g., (Jun, Kim, 1994; Kumar, Gardoni, Sanchez-Silva, 2009; Monteith, 1984; Val, Stewart, 2003; Val, Stewart, 2005), the methods for calculating parameters of corrective maintenance costs are discussed. The calculation methods for calculating the logistic support costs of the corrective maintenance were presented, i.a. in (PN-EN 60300-3-3, 2001) and (Kumar, Chattopadhyay, Pannu, 2004), while the method for estimating the logistic support costs of preventive maintenance are covered, e.g., in (Ntuen, 1985). The studies (Hinow, Waldron, Muller, 2008; Norsok Standard: O-CR-001, 1996; Norsok Standard: O-CR-002, 1996; Parra, Moreu, Gomez, Gonzalez, 2009; PN-EN 60300-3-3, 2001) present methods for calculating the cost components and parameters of the production loss caused by object damage.

It is worth emphasising the existing gap in scientific studies, apart from few exceptions, addressing LCC estimation that would comprehensively analyse the problem of exploitation costs calculation for each technical object from the position of its purchaser.
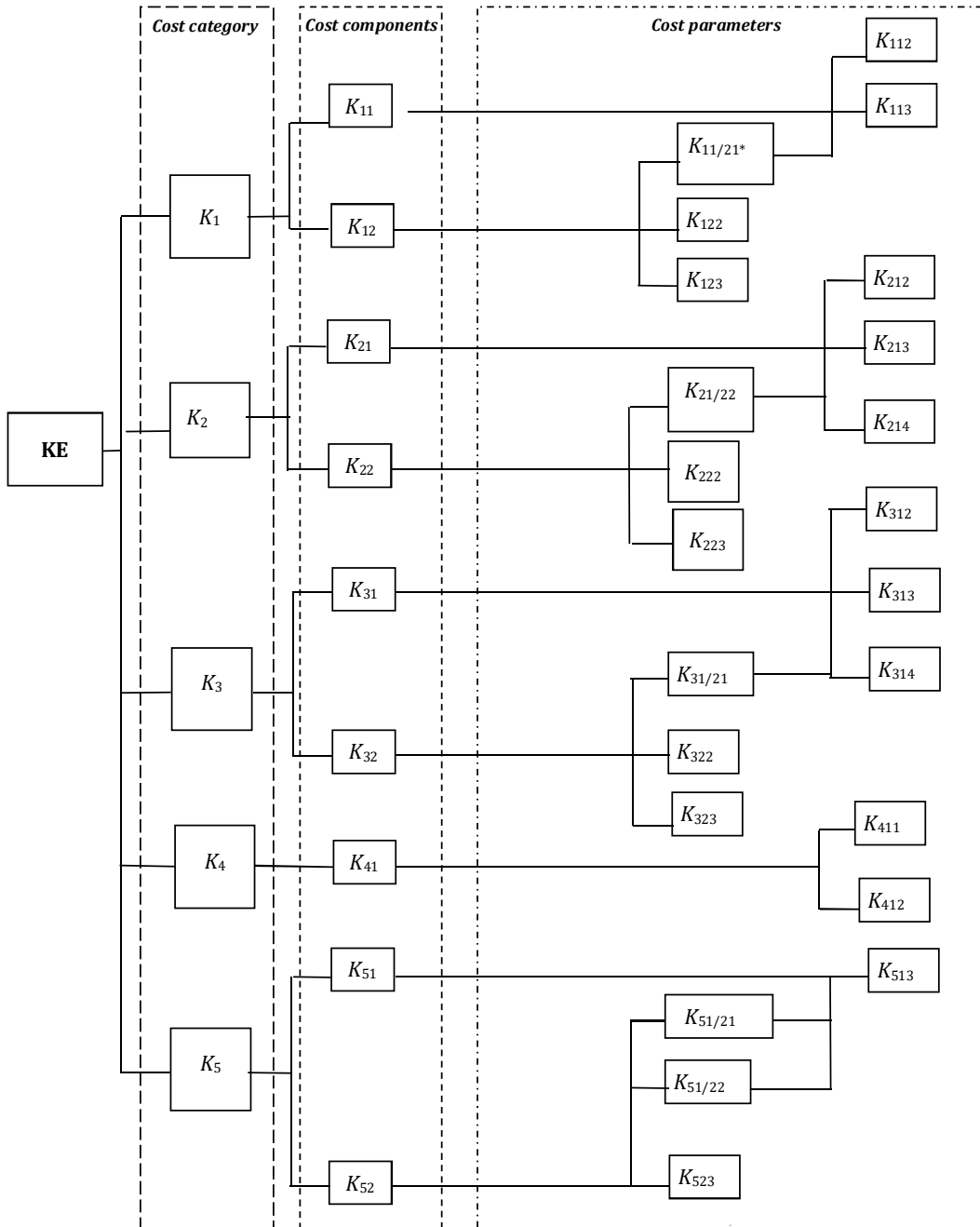
Description of the figure:

$K_{11/21*}$ – the first parameter of both the first and the second cost component assigned to the first exploitation cost category (in this case, it is the time of the vehicles' operation, necessary to determine the salaries of employees operating the technical object and the cost of diesel consumption

KE – exploitation costs covered during the full life cycle of a technical object
K_1 – operation costs covered during the full life cycle of a technical object
K_{11} – costs of salaries (labour) of the personnel using the technical object
$K_{11/21}$ – work or exploitation time per unit of time, e.g., mileage per unit of time
K_{112} – cost of human labour per unit of time
K_{113} – number of people using an object
K_{12} – energy consumption costs
K_{122} – purchase price of an energy unit
K_{123} – energy consumption per unit of time
K_2 – costs of performing preventive maintenance
K_{21} – costs of service personnel remuneration
$K_{21/21}$ – number of preventive maintenance
K_{212} – number of people performing preventive maintenance
K_{213} – unit duration of preventive maintenance
K_{214} – labour cost of service personnel per unit of time
K_{22} – costs of consumables and spare parts used in the implementation of preventive maintenance
K_{222} – price of the r-th spare part or a consumable material used in preventive maintenance
K_{223} – number of the r-th spare part or a consumable material used in preventive maintenance
K_3 – costs of performing corrective maintenance
K_{31} – costs of service personnel remuneration
$K_{31/21}$ – number of performed corrective maintenance (damage)
K_{312} – number of people performing corrective maintenance
K_{313} – unit duration of corrective maintenance
K_{314} – labour cost of service personnel per unit of time
K_{32} – costs of consumables and spare parts used in the implementation of corrective maintenance
K_{322} – price of the r-th spare part or a consumable material used in corrective maintenance
K_{323} – number of the r-th spare part or a consumable material used in corrective maintenance
K_4 – costs of logistic support for corrective maintenance
K_{41} – costs of maintaining the r-th part in stock in a warehouse per unit of time
K_{411} – unit cost of maintaining the r-th part in a warehouse
K_{412} – number of spare parts to be kept in stock in case of damage
K_5 – other costs related to the damageability of a technical object than the costs of corrective maintenance
K_{51} – costs of production loss caused by an object damage
$K_{51/21}$ – object downtime due to damage per unit of time
$K_{51/22}$ – number of performed corrective maintenance (damage)
K_{513} – size of the production lost as a result of damage
K_{52} – penalty costs resulting from unplanned downtime
K_{523} – unit penalty costs related to the non-performance of tasks

Figure 2. The example of the exploitation costs structure of a technical object from the user's perspective

Source: author's work.

In the existing procedures, the measurement of costs is usually performed based on average parameter values/sizes resulting from the analysis of the previous years. On their basis, the annual cost component is calculated. The cost component value is constant (the same for the first and the final year of the object's exploitation). However, these costs are not a determined value but a random variable. For this reason, it is necessary to use these methods that allow estimating exploitation costs to take into account their variability over time resulting from gradual changes in the object's parameters caused by the processes of technical wear.

Research methods

Method for forecasting the exploitation costs of a technical object taking into account the variability of costs overtime consists of 10 stages (figure 3). In the method, while estimating cost parameters, the central tendency values and lower and upper quantiles are used, which allows estimating costs in three variants: the expected variant (e.g. modal), the optimistic variant and the pessimistic one.

The starting point is defining the exploitation cost breakdown structure and collecting the essential data to estimate the exploitation cost parameters. These data should be obtained from the enterprises exploiting technical objects of a given (the same) class or technically similar to the object intended to be purchased by a decision-maker. Next, the equal length (span) of time periods should be determined. The unit of timescale can take the form of, e.g., a calendar month, a mileage (e.g. every 10,000 km), etc. The longer the analysis period of the objects, the larger the number of time intervals (the longer the time series). Estimating the parameter mean value for the time interval remains the next step of the method, followed by verifying whether the parameter mean value depends on time. Suppose a given cost parameter does not depend on time. In that case, the probability distribution should be determined for the mean parameter values, and the central tendency values should be calculated along with the upper and lower quantiles. Otherwise, i.e. if a given cost parameter is time-dependent, the trend line should be fitted to the parameter mean values specified for the defined time intervals and the trend line equation should be determined as well as the upper and lower quantile of the parameter should be estimated for each time interval. The subsequent step is focused on verifying whether the upper and lower quantile of the parameter is time-dependent. Suppose the values of upper and lower quantiles of the parameter are not time dependent. In that case, the probability distribution for these parameter values should be determined,
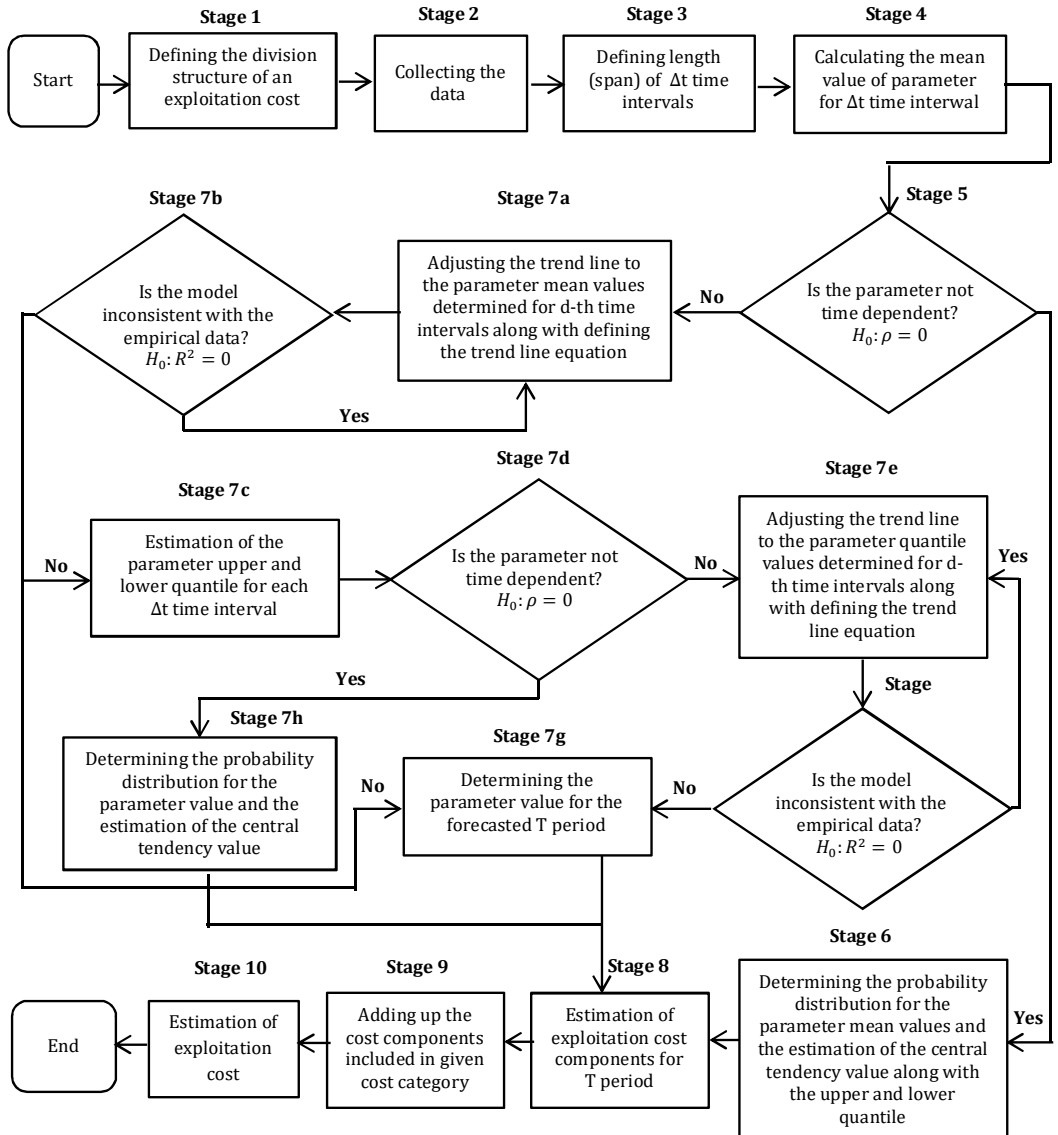
Figure 3. An algorithm followed in the method for forecasting the exploitation costs
            of a technical object

Source: author's work based on Dziaduch, 2020a.

and the central tendency values should be calculated. Otherwise, i.e. if the
values of upper and lower quantiles of the parameter remain time-depend-
ent, the trend line should be fitted to the value of parameter quantiles identi-
fied for the defined time intervals, and its equation should be determined.

For the parameter mean values and/or for the values of lower and upper quantiles to which the trend line was fitted, the parameter values should be determined for the expected period of the object life cycle. The parameter values estimated in this way should be used in estimating cost components based on analytical expressions defined in the literature or developed by the researcher.

The particular stages of the method are described in detail in (Dziaduch, 2020a).

It is worth indicating that the exploitation costs are incurred at various time intervals. During this time, the value of money changes (from the present perspective, this value declines along with time). This is caused, firstly, by inflation, i.e. the annual increase in the prices of goods and services in the economy, and secondly, it is always an alternative investment to deposit money in the bank at a certain interest. Therefore, in order to maintain the cost value comparability overtime throughout the entire life cycle of a technical object, a discount calculation can be used based on which the value of money is made real regardless of when it is spent. In such a case, it could be the last step in the cost forecasting method presented above. The methods of calculating future costs for a given moment, i.e. at the time of conducting the analysis, are presented, i.a. in the studies (Alaska Department of Education and Early Development, 1999; Anders, Endrenyi, 2005; Fuller, Petersen, 1996; Goedeckeb, Therdthianwong, Gheewa, 2007; Hennecke, 1999; Parra, Crespo, Cortes, Fyoueroa, 2006; Parra, Moreu, Gomez, Gonzalez, 2009).

Application of the method for forecasting the exploitation costs of technical objects

Object and research period

The study covered eight single-mode X series rail buses produced by the same manufacturer. Three vehicles were purchased directly from the manufacturer, whereas the remaining five were from the manufacturer's agent, which significantly impacted the costs incurred (there are differences, e.g., in purchase costs or maintenance costs). These vehicles are used by the carrier, alternately on the same routes, in similar exploitation conditions.

The analysis period covered 1,295 calendar days, from December 14, 2013, until June 30, 2017 (figure 4). During this period, it was possible to determine the technical and economic parameters from the 1st to the 50th month of the rail buses exploitation.

The objects covered by the research included both new rail buses and also the ones previously exploited by another railway carrier. The hand-

ing-over of rail buses to the analysed enterprise took place at various times; hence the exploitation time covered by the study is not the same for all the analysed rail buses (Figure 4). For buses 1, 2 and 3, determining the cost parameters was possible from the 9th till the 50th month of exploitation. However, for the buses No. 4 and 5, it was possible from the 1st till the 19th month of exploitation, whereas for other objects from the 1st till the 16th, 13th and 12th month, i.e., for buses 6, 7 and 8, respectively.
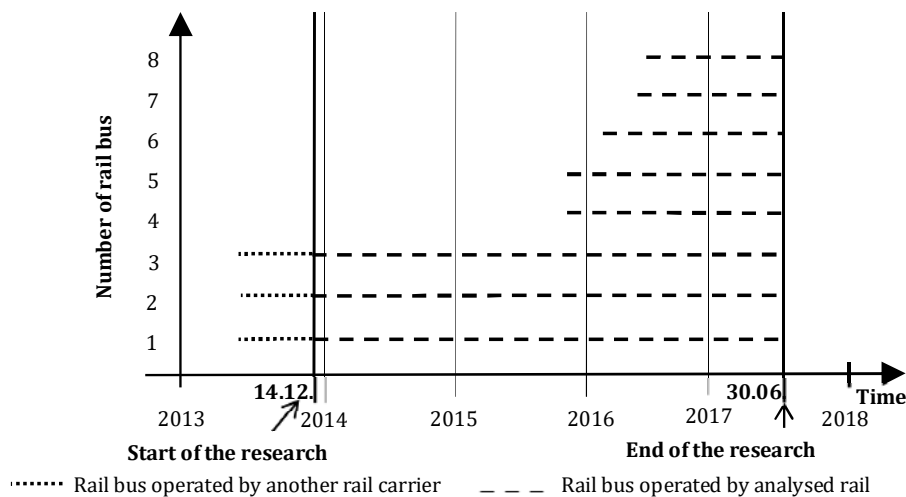

Figure 4. Time schedule of performed research analysis

Source: author's work.

Assumptions

The exploitation cost structure is described by the following correlation:

$$KE = KU + \sum_{i=1}^{I} KOP_i + KOK ,\qquad (1)$$

where:

KE –　exploitation costs covered during the full life cycle of a rail bus,

KU –　operation costs covered during the full life cycle of a rail bus,

KOP_i –　costs of performing the i-th kind of preventive maintenance in the life cycle of a rail bus,

KOK –　corrective maintenance costs incurred throughout the life cycle of a rail bus.

The presented article does not describe the time and cost parameters necessary for the operation cost analysis, as they have been analysed in detail and estimated in the study (Dziaduch, 2020b). However, these parameters

were taken into account when estimating the exploitation cost of rail buses (formula 1).

The costs incurred while performing preventive maintenance inspections of rail buses are the sum of the costs incurred performing 8 types of inspections, i.e. PU1, PU2-1, PU2-2, PU2-3, PU3-1, PU3-2, PU4 and PU5 (Dziaduch, I., 2011b). All vehicle inspections are repeated in a cyclical manner. They are performed after completing a determined number of units of a vehicle working time, expressed in kilometres covered by the vehicle, its hours of operation or after a given calendar operation time (days, months, years), whichever comes first. The collected data allowed a detailed analysis of PU1, PU2-1, PU2-2 and PU2-3 level inspections as well as a general analysis of PU3 rail bus preventive maintenance inspections. Due to a short operation time, the PU4 and PU5 vehicle levels were not inspected as yet. PU1 and PU2 time-cost parameters were estimated based on the collected data, while the information on PU3, PU4 and PU5 time-cost parameters was collected in the course of interviews with the enterprise employees.

The analysis and assessment of the corrective maintenance process was possible to a limited extent, e.g., due to the lack of information on the duration of corrective maintenance and the number of people performing it. This mainly resulted from the fact that the majority of corrective maintenance was carried out during the preventive maintenance. Based on the available information, only the unit costs of removing the recorded damage and the duration of corrective maintenance were determined.

The maintenance cost was estimated adopting the following assumptions:

1. The preventive maintenance of PU1 is performed by 2 in-house service employees, both during and after the 3-year vehicle warranty period;

2. Preventive maintenance of PU2 during the vehicle warranty period is performed for a fee by the vehicle manufacturer's service. The cost of this inspection for 1-3 vehicles amounts approximately to PLN 15,000, and for 4-8 vehicles – PLN 33,000. After the warranty period expires, the preventive maintenance of PU2 is performed by 2 in-house service employees. Due to the fact that after the warranty period expiry, the parameters for PU2-1, PU2-2 and PU2-3 are almost identical, they were not determined separately for each type of PU2 preventive maintenance.

3. Preventive maintenance of PU3 is performed for a fee by the vehicle manufacturer's service, both during and after the warranty period. The parameters referring to these types of preventive maintenance are as follows:
   – The maintenance time is 15 and 35 working days for PU3-1 and PU3-2, respectively;

- The unit cost of PU3-1 and PU3-2 maintenance is approximately PLN 57,000 and PLN 340,000, respectively;
- PU3-1 maintenance is performed, on average, after every 19 months of exploitation, while PU3-2 service is performed, on average, after every 36 months of the vehicle exploitation.

4. Preventive maintenance of PU4 and PU5 is performed for a fee by the vehicle manufacturer's service, both during and after the warranty period. The parameters referring to these types of preventive maintenance are as follows:
   - PU4 duration is 45 working days, and PU5 – 60 working days;
   - The unit cost of PU4 maintenance is PLN 800,000, while PU5 – PLN 2,500,000;
   - The moments of performing PU3 maintenance were considered the basis for determining the moment of carrying out PU4 and PU5 maintenance.

5. The central tendency measure is the expected value of E(x) parameters;
6. The adopted horizon of cost forecasting is 50 months;
7. The exploitation month is not the same as the calendar month;
8. When calculating the number of days in the month of exploitation, it was adopted that the calendar year has 365 days;
9. Costs are not discounted;
10. The structure of operating costs consists of seven components and nineteen cost parameters included in them (figure 5).

Cost components were defined based on the following formulas:

$$K_{21} = K_{21/21} \cdot K_{212} \cdot K_{213} \cdot K_{214}, \tag{2}$$

$$K_{22} = K_{21/21} \cdot K_{222}, \tag{3}$$

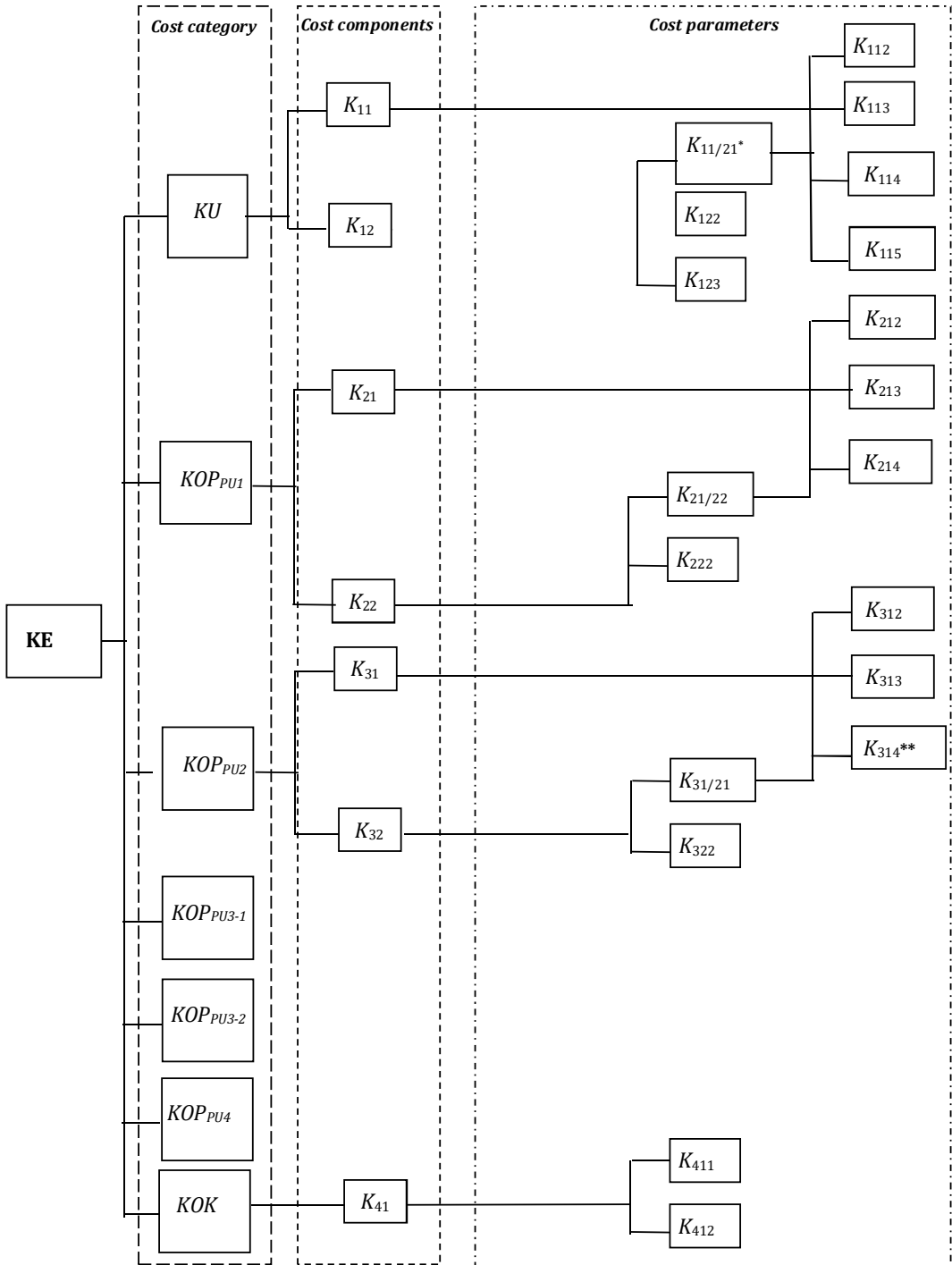$$K_{31} = K_{31/21} \cdot K_{312} \cdot K_{313} \cdot K_{314}, \tag{4}$$

$$K_{32} = K_{31/21} \cdot K_{322}, \tag{5}$$

$$K_{41} = K_{411} \cdot K_{412}, \tag{6}$$

At the significance level of $\alpha=0.1$, the statistical significance of the trend model was verified.

At the significance level of $\alpha=0.05$, the hypothesis about the absence of correlation between the cost parameter and the exploitation time was verified.

Description of the figure:

$K_{11/21*}$ – the first parameter of both the first and the second cost component assigned to the first exploitation cost category (in this case, it is the time of the vehicles' operation, necessary to determine the salaries of employees operating the technical object and the cost of diesel consumption)

$K_{314**} = K_{214}$

K_{11} – costs of salaries (labour) of the personnel using the technical object

$K_{11/21}$ – exploitation time, e.g., mileage per unit of time

K_{112} – cost of conductors' work per unit of time

K_{113} – number of conductors in a vehicle

K_{114} – cost of train drivers' work per unit of time

K_{115} – number of train drivers in a vehicle

K_{12} – cost of diesel fuel consumption

K_{122} – purchase price of a litre of diesel

K_{123} – diesel fuel consumption per unit of time

K_{21} – costs of service personnel remuneration for performing PU1 maintenance

$K_{21/21}$ – number of PU1 preventive maintenance

K_{212} – number of people performing PU1 preventive maintenance

K_{213} – unit duration of PU1 preventive maintenance

K_{214} – labour cost of service personnel per unit of time

K_{22} – costs of consumables and spare parts used in the implementation of PU1 preventive maintenance

K_{222} – unit cost of consumables and spare parts used in the implementation of PU1 preventive maintenance

K_{31} – costs of service personnel remuneration for performing PU2 maintenance

$K_{31/21}$ – number of PU2 preventive maintenance

K_{312} – number of people performing PU2 preventive maintenance

K_{313} – unit duration of PU2 preventive maintenance

K_{314} – labour cost of service personnel per unit of time

K_{32} – costs of consumables and spare parts used in the implementation of PU2 preventive maintenance

K_{322} – unit cost of consumables and spare parts used in the implementation of PU2 preventive maintenance

K_{41} – costs of performing corrective maintenance

K_{411} – number of performed corrective maintenance (damage)

Figure 5. The structure of costs distribution of a rail bus exploitation adopted for calculations
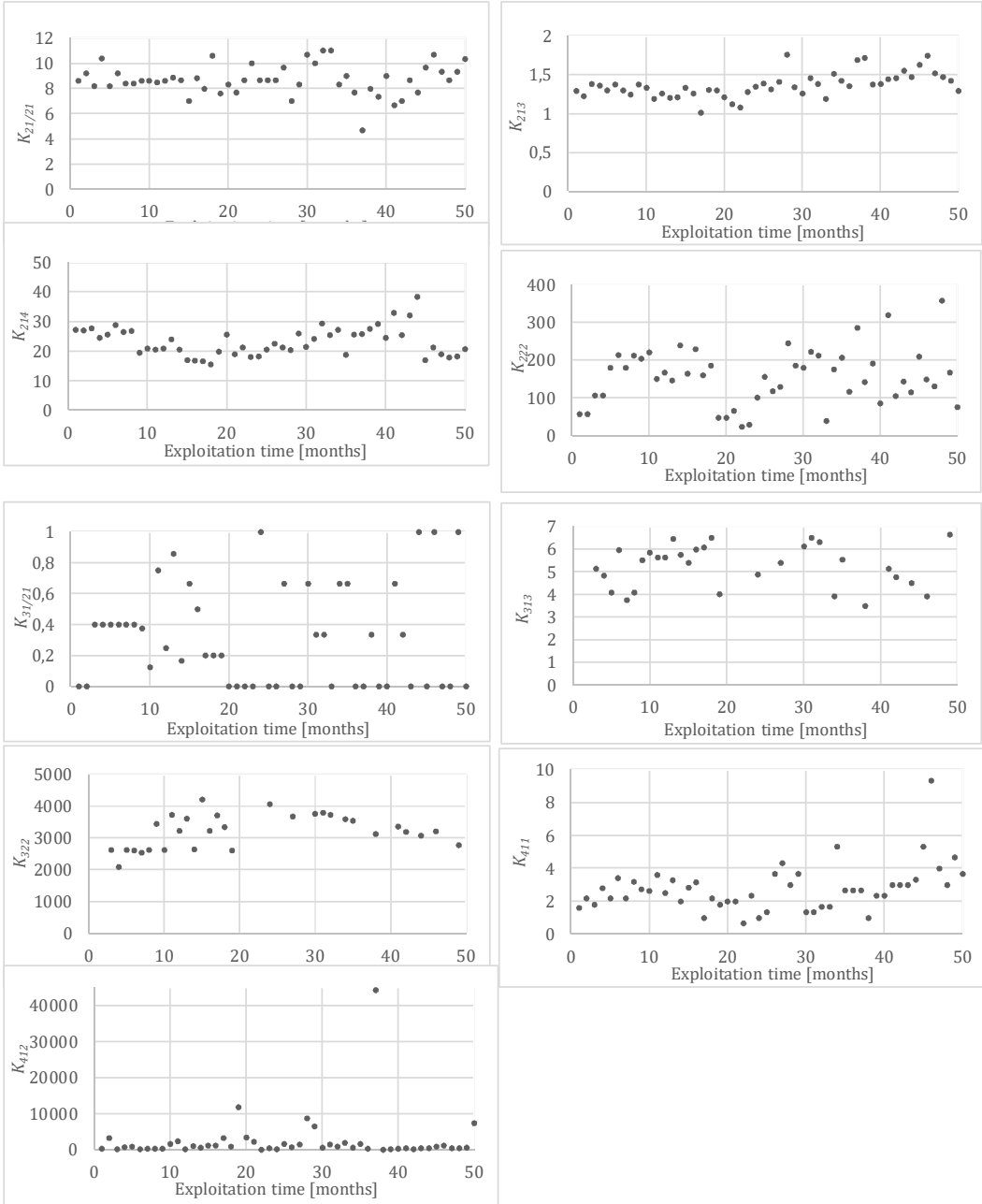
Source: author's work.

Figure 6. Data for the time series analysis covering a given maintenance cost parameter of rail buses

Source: author's work.

The accuracy degree of the exploitation cost forecast was measured using the ex-post relative forecast error from the formula (Cieślak, 2005):

$$\gamma_t = \frac{KE_t - KE_t^{rz}}{KE_t} \cdot 100, \qquad (7)$$

where:
γ_t –   ex-post relative forecast error at the end of Δt time interval,
KE_t –   forecasted operation cost value at the end of Δt time interval,
KE_t^{rz} –   actual value of the vehicle exploitation costs in Δt time interval.

The statistical data analysis was performed using the functions and commands available in Microsoft Excel. Weibull++ application was also used, which allowed, e.g., as follows:
• developing histograms and cumulative distribution functions for random variables,
• verification of hypotheses (carried out using Spearman's rho ρ correlation coefficient) in the form of distributions of the analysed random variables,
• estimation of the unknown distribution characteristics.

Results of the research

For the purpose of exploitation cost calculation, time series for cost parameters were developed. These series were constructed by averaging the cost parameters per month of rail bus exploitation. Figure 6 presents the data necessary to analyse the time series of the maintenance cost parameters.

The list of parameters necessary to estimate the cost components described by formulas (2-6) is presented in table 1.

The collected material analysis shows that most exploitation cost parameters do not depend on time. These parameters can be modelled using normal and log-normal distribution – high values of the Spearman's rank correlation coefficient (ρ) were obtained, ranging from 0.88 to 0.99. For the probability distribution fitting of the parameters, the expected value $E(x)$ and the lower and upper quantiles for q=0.05, Since the PU2 maintenance does not take place in every time interval (they are performed cyclically), it was adopted that $K_{31/21}$ parameter is described with the normal distribution. Having adopted this assumption, the average number of PU2 maintenance services is 0.307, with a standard deviation of 0.328. For the above-mentioned reason, it is not justified to estimate the values of both lower and upper quan-

Table 1. Parameters of the maintenance cost components for time intervals presented as the months of vehicle exploitation

		$K_{21/21}$	K_{213}	K_{214}	K_{222}	$K_{31/21}$	K_{313}	K_{322}	K_{411}	K_{412}
Correlation coefficient (r)	Mean values (x)	0,01	0,54	0,06	0,15	0,007	-0,06	0,23	0,36	0,11
	$F(x_{0,95})$		0,30						0,07	
	$F(x_{0,05})$		0,55						0,54	
$H0 : \rho=0$ dla $\alpha=0,05$	Mean values (x)	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes
	$F(x_{0,95})$		No						Yes	
	$F(x_{0,05})$		No						No	
Type of probability distribution	Mean values (x)	Normal		Log-normal	Normal		Normal	Normal		Log-normal
	$F(x_{0,95})$								Normal	
	$F(x_{0,05})$									
Distribution matching (ρ)	Mean values (x)	0,97		0,99	0,99		0,98	0,98		0,99
	$F(x_{0,95})$								0,95	
	$F(x_{0,05})$									
Central tendency values	E(X)	8,70		23,24	155	0,307	5,3	3219	4,48	2348
	$M_0(X)$	8,70		21,88	155		5,3	3219		59
	$M_e(X)$	8,70		22,76	155		5,3	3219		686
Upper and lower quantile	$F(x_{0,95})$	10,68		31,87	278	0,383	6,8	4115		9054
	$F(x_{0,05})$	6,71		16,25	33	0,231	3,7	2323		52
Trend line equation	Mean values (x)		$x_t=1,1536+0,0719\ln(t)$						$x_t=1,5022+0,4271\ln(t)$	
	$F(x_{0,95})$		$x_{0,95t}=1,4381+0,0043t$							
	$F(x_{0,05})$		$x_{0,05t}=0,9119+0,0977\ln(t)$						$x_{0,05t}=-0,8125+0,7114\ln(t)$	
$H_0 : R^2 = 0$ dla $\alpha = 0,1$	Mean values (x)		No						No	
	$F(x_{0,95})$		No							
	$F(x_{0,05})$		No						No	

Source: author's work.

tiles. The value of the lower quantile would amount to 0, meaning that PU2 maintenance service is not present during the vehicle exploitation period. Instead of the values of lower and upper quantiles, the 90% confidence interval was estimated for the average number of PU2 maintenance services.

The data analysis also indicates that the average values of two exploitation cost parameters, i.e. K_{213} – unit of time of PU1 preventive maintenance and K_{214} – the number of corrective maintenance (damage), depend on the rail buses exploitation time and the parameters of the logarithmic trend lines adjusted to them are statistically significant. The values of both lower and upper quantiles of the unit of time of PU1 maintenance service also depend on the vehicle exploitation time. The analysis of K_{213} lower quantile values indicates a logarithmic trend, whereas the analysis of upper quantile values of this cost parameter presents a linear trend. In both cases, the parameters of fitted models are statistically significant. In addition, the data show that the values of lower quantiles of the number of damages also depend on the vehicle exploitation time and the parameters of the logarithmic trend model adjusted to them are statistically significant. However, there is no statistically significant correlation between the values of upper quantiles of the number of damages and the vehicle exploitation time. The analysis shows that a normal distribution can describe this variable – a high value of the Spearman's rank correlation coefficient ρ was obtained, amounting to 0.95.

Figure 7 shows the forecast values of exploitation costs against the background of real costs in the period covered by the study. Due to the significant difference in the amount of costs incurred for PU2 maintenance, the exploitation cost estimation was performed separately for vehicles 1-3 and 4-8.

The relative errors made when measuring operation costs at the end of time interval, i.e. the last period in which the actual costs were recorded, are summarised in table 2. The analysis shows that the forecast error for the majority of the studied cases is lower than 10%. The average error in the exploitation cost forecast was approx. 4.9%.

Conclusions

The exploitation costs for the single-mode X series rail buses were calculated in the article. The cost calculation was performed based on technical and economic data collected from December 14, 2013, till June 30, 2017. These data allowed analysing rail buses' operation and maintenance process and determining the cost parameters necessary to calculate the exploitation costs. The cost forecast was prepared in accordance with 10 stages of the method for forecasting the exploitation costs of a technical object, taking into

Table 2. Relative errors in measuring exploitation costs of rail buses

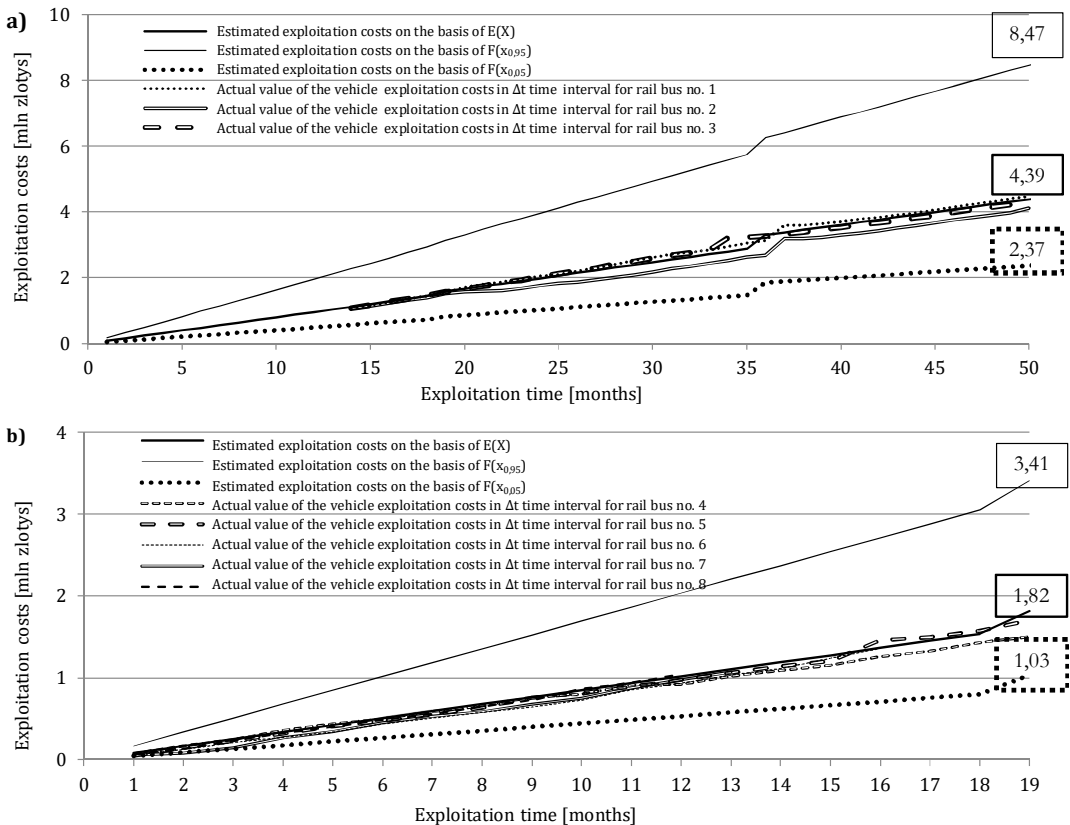| Rail bus number	Last month of the rail bus exploitation T	KE_t^{rz}	KE_t	γ_t
1	50	4 474 901,00	4 387 329,00	-0,02
2	50	4 118 997,00	4 389 392,00	0,06
3	50	4 302 119,00	4 389 392,00	0,02
4	19	1 502 556,00	1 811 856,00	0,17
5	19	1 697 219,00	1 811 856,00	0,06
6	16	1 360 361,00	1 363 534,00	0,00
7	13	1 070 808,00	1 105 428,00	0,03
8	12	1 041 423,00	1 019 539,00	-0,02

Source: author's work.

Figure 7. Cumulative exploitation costs of rail buses in the analysed period presented as the months of exploitation for vehicles: a) 1-3, b) 4-8

Source: author's work.

account their variability over time. The verification conducted regarding the correctness of the findings was performed for the exploitation costs estimated based on the expected value of *E(x)* cost parameters. The obtained cost forecast results were compared with the real costs incurred by the carrier during the last analysed month of the vehicle exploitation. The degree of accuracy of the exploitation cost forecast was measured using ex-post relative forecast error. The average error was 4.9%. This means that the real cost values do not differ much from the forecasted values. Therefore, it can be concluded that the prognostic value of the method is relatively high.

A great advantage of the discussed method is the possibility of determining costs in the adopted exploitation period, not only in the most probable variant (based on *E(x)*), but also in the optimistic and pessimistic ones. The optimistic variant of the forecast means the minimum exploitation cost to be incurred by the object user, while the pessimistic variant of the forecast determines the maximum value of costs to be covered by the user in the course of the object exploitation. The costs in the optimistic variant are determined based on the values of lower quantiles of cost parameters; in turn, following the pessimistic variant of the forecast, the values of upper quantiles of cost parameters are taken into account.

The method of the exploitation cost forecasting of a technical object, taking into account cost variability over time, can represent the tool supporting investment decisions related to purchasing a new technical object. From the perspective of a technical object potential user, the estimated exploitation costs of such an object, along with the costs of its acquisition, make up the life cycle cost. This method eliminates the acquisition of technical objects that are cheap in terms of purchase costs, however, expensive in exploitation.

The economic life cycle analysis of technical objects presented in the article represents one of the tools used in assessing the degree of implementation of sustainable development principles in transport. However, the assessment of applying the philosophy of sustainable development in practice is based not only on the knowledge provided by the economic life cycle analysis but also on the knowledge of environmental and social assessment of object life cycle. Therefore, the analysis of the life cycle of rail buses taking into account environmental and social aspects is the next stage of the research work conducted by the author of this article.

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